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Classifying System for Façades and Anomalies

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ABSTRACT

Façades play an important role in buildings' energy demand, and their state of conservation obviously influences thermal performance. The energy performance gap in existing residential buildings due to façade conservation status has not been analyzed in depth. In order to facilitate the systematic analysis of this influence, a system for classifying façades and their corresponding anomalies was developed for the first time. The classification system includes 23 types of façades and eight types of anomalies. It was verified by a panel of experts, and a case study was carried out with a sample of 154 buildings. An analysis of the results showed that the classification system is useful for a future analysis of the energy performance gap in existing residential buildings

CE Database subject headings:

classification, anomalies, residential buildings, Spain

Author keywords:

residential building stock, façade, anomaly, classification system

1. INTRODUCTION

Interest in improving buildings' energy performance has been growing, as buildings are responsible for 41% of total final energy consumption in Europe (European Union 2013). In order to achieve the European Union's "20-20-20" energy efficiency target,

two documents have been published recently: the European Commission's Energy Efficiency Plan 2011 (European Commission 2011) and Directive 2012/27/EU on energy efficiency (European Union 2012). Both documents highlight construction as the biggest potential sector for energy saving. According to the European Commission (European Commission 2006), potential energy savings of 27% can be made in residential buildings. To reach energy efficiency targets, Horizon 2020, the European Union Framework Programme for Research and Innovation for 2014 to 2020, stresses the need to close the gap between the predicted and actual energy performance of existing buildings (European Commission 2014).

According to Balaras et al. (2005), the existing building stock in Europe is estimated at 150 million dwellings. Approximately 70% of the residential building stock is over 30 years old, and about 35% is more than 50 years old. In Spain, the existing residential building stock stood at around 9.7 million dwellings, about 56% of which were built before 1980 (Instituto Nacional de Estadística 2013), when the NBE CT-79 (Spain 1979) basic building regulations on thermal conditions in buildings came into effect (Gangoellés and Casals 2012).

NBE CT-79 (Spain 1979) establishes five areas (V-Z) according to the mean minimum temperature in January, and uses this classification to set maximum heat transmission coefficients for individual closures (Gangoellés and Casals 2012). NBE CT-79 (Spain 1979) was repealed by the Technical Building Code (Spain 2006), which was adopted as a result of the transposition of 2002/91/EC, the first Energy Performance of Buildings Directive (EPBD) (European Union 2002). The Technical Building Code (Spain 2006) establishes five areas (A-E) according to the winter climate zone, taking into account solar radiation and heating/cooling degree-days based on 20°C. This classification is used to set the maximum heat transmission coefficients for individual closures (Gangoellés and Casals 2012). Table 1 shows typical *U-values* for the façades of these buildings.

The breakdown of total household energy consumption by end-use in the European Union is as follows: 68% for space heating, 12% for water heating, 4% for cooking and 15% for lighting and electric appliances (Lapillonne et al. 2012). The breakdown of the total energy consumption by end-use in Spain is as follows: 47% for space heating, 27.4% for water heating, 24.5% for lighting and electric appliances, and 1.1% for space cooling (IDAE 2011). As observed, space heating is responsible for a high proportion of energy consumption in residential buildings, and consequently has considerable potential for energy saving. Two methods can achieve energy savings in residential building stock: (1) reduce the energy demand by modifying construction elements (passive method), and (2) enhance the energy efficiency of heating, ventilation, and air conditioning systems (active method).

In existing residential buildings, the gap between predicted and actual energy performance due to façade state and conservation status has not been analysed in depth. According to Williamson (2010), deterioration over time could have a significant impact on energy consumption. However, this is not a well-researched issue, and no thermal simulation program takes this or other known unknowns into account.

Façades play an important role in buildings' energy demand. To date, evaluations of the thermal performance of façades in existing buildings have tended to focus on the composition of the layers and are based on a building's age rather than the envelope degradation and the façades' conservation status. However, according to Rodrigues et al. (2013), the conservation state of the building envelope might have a significant effect on a building's thermal behaviour. To analyse the influence of envelope degradation on buildings' energy performance, first the relationship between types of façades and the types of anomalies that may affect an envelope's conservation status must be established. No relevant contributions on this area were found in the literature. Thus, the aim of this paper was to develop a classification system for types of façades and the types of anomalies that can affect conservation status, to facilitate a systematic analysis of the influence of closures' state of conservation on the thermal performance of buildings in the Spanish housing sector.

The method used to determine and validate the classification system is explained in the second section following this introduction. In the third section, a case study is presented to verify the system. Finally, the conclusions are given in the fourth section, and suggestions are made for future research.

2. METHOD

First, a thorough literature review was carried out on existing classifications of façades, and of the anomalies that can damage these closures. As a result of this analysis, several types of façades and anomalies were proposed. The proposal was later refined and validated by a panel of experts. Then, again with the help of experts, a system was established for classifying façade types and associated types of anomalies that affect the state of conservation of closures in existing residential buildings. Finally, a case study was performed to verify the approach (Fig. 1).

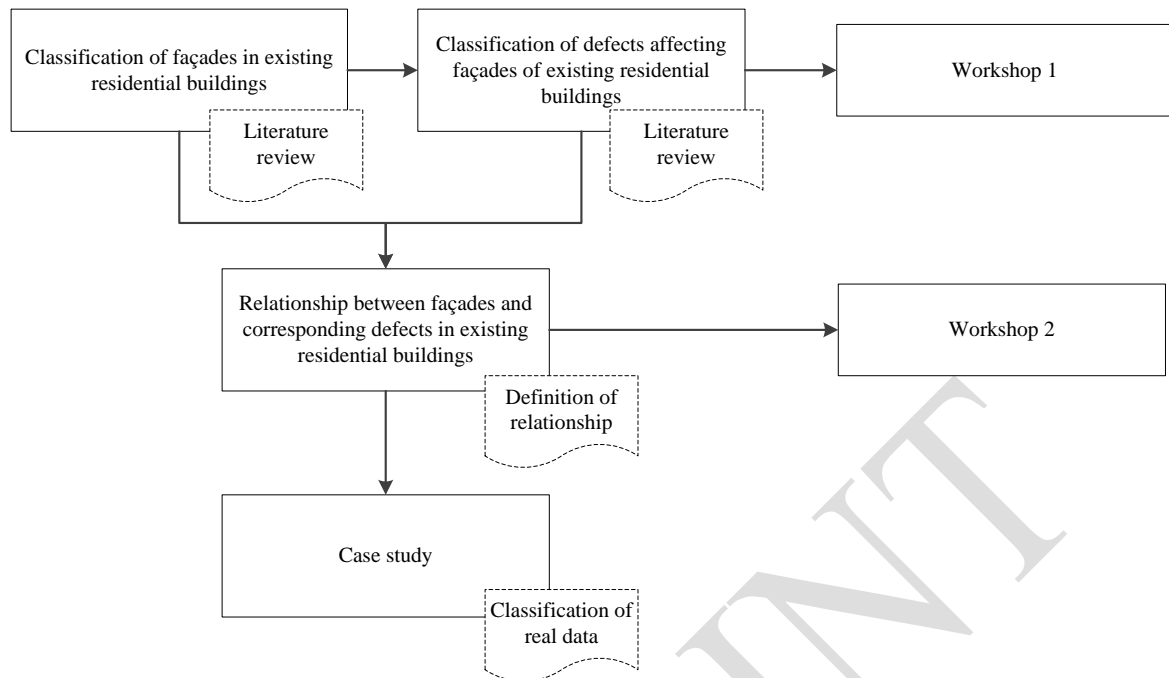


Fig. 1. Research methodology

2.1 CLASSIFICATION OF FAÇADES IN EXISTING RESIDENTIAL BUILDINGS

The first step in characterising the opaque part of façades in existing Spanish residential buildings was to analyse national and regional regulations and codes for buildings and construction processes. According to Jørgensen (2011), these regulations and codes do not provide a classification system, but they do describe Spanish construction systems in detail. A catalogue of building elements was developed (IETcc 2010) to promote compliance with the general habitability design requirements of the Technical Building Code in Spain (Spain 2006). Façades were categorised into twenty types according to the main characteristics of the wall covering, air cavity and insulation. The types vary according to the main skin's material, the inner skin's material, the existence of intermediate cladding, the existence of inner cladding, and the existence and type of air cavity and internal partitions. Spanish building types were characterised by the *Instituto Valenciano de la Edificación* (IVE) as part of the Tabula Project (Loga et al. 2012) for energy performance assessment of national building stock. In addition, a catalogue of construction solutions for energy building renovation (Valencia Institute of Building 2011) has been drawn up by the IVE, detailing a wide range of construction elements that can be found in thermal envelopes in Spanish buildings from the 1940s to the 1980s. The catalogue contains a classification of types of existing façades according to the number of skins, air cavity, insulation and wall covering.

In the second step, existing classifications of façades in the housing stock were analysed. First, classifications related to the construction industry were reviewed. Several classifications such as OmniClass (OmniClass 2006) and UniClass (Crawford et

al. 1997) have been developed that take as a reference the standard ISO 12006-2:2001 (ISO 2001), where the “element” is the basis for classification. According to Jørgensen (2011), “element” is defined as part of a construction entity that, alone or in combination with other parts, fulfils a predominant function. Both UniClass and OmniClass are faceted classifications for the architectural, engineering and construction industry that are designed within the parameters of ISO 12006-2 (ISO 2001) and organised in tables. OmniClass (OmniClass 2006) is focused on US terminology and practise, and consists of fifteen tables representing different facets of construction information. UniClass (Crawford et al. 1997) is the equivalent classification for the United Kingdom. It is also structured into fifteen tables representing different aspects of construction information. The Danish DBK classification (BIPS 2006) is also based on ISO 12006-2:2001 parameters, but the top part of the table is organised by systems and the function of components are listed in a sub-table (Jørgensen 2011). Other existing classifications are not based on ISO 12006-2:2001 (ISO 2001). This is the case of UniFormat (The Construction Specifications Institute 2010) in the United States of America and Canada, and BSAB 96 (Svensk Byggtjänst 1999) in Sweden. UniFormat (The Construction Specifications Institute 2010) is a standard method for organising construction information around the physical part of systems and assemblies, which are characterised by their function without identifying the technical or design solutions that may have been used. According to Jørgensen (2011), BSAB 96 (Svensk Byggtjänst 1999) has separate entries for the classification of composite elements and that of systems compared to elements, and consequently there are conflicting classification requirements.

The third step involved a literature review. Monjo (2005) carried out a general analysis of the evolution of construction systems for buildings’ closures. Adell and Vega (2005) undertook a specific analysis of types of reinforced brick façade (supported, suspended and prefabricated). Eicker et al. (2008) reviewed façade systems and the energy performance of single and multiple-skin glazed façades with sun-shading systems in non-residential buildings. Chan et al. (2009) evaluated the energy performance of double-skin façades with various configurations including glazing type, glazing position and glazing layers. Some authors focused their research on residential buildings. Chandra (1980) classified four walls in hot dry climates on the basis of their thermal performance index (precast and cast-in-place walls). In order to analyse the influence of external walls’ thermal inertia on the energy performance of well-insulated buildings, Aste et al. (2009) established twenty-four construction systems for opaque vertical walls grouped into three categories: (1) single layer massive walls, (2) walls with insulation outside, in the middle, inside or on both sides, and (3) light walls mainly based on insulation materials. Pulselli et al. (2009) evaluated three building envelope technologies from an environmental perspective, namely: a traditional air-cavity wall, a plus-insulated wall (with an external cork covering), and a ventilated wall (with external brick panels fixed on extruded frames). To gain fundamental insight into how to improve insulation performance with arrangements of wall layers, Bond et al. (2013) defined four primary configurations of multi-layered walls with fixed volumes of insulation and thermal mass, in which only the layer distribution varied. Sadineni et al. (2011) reviewed building envelope components for passive building energy savings. They defined four advanced wall technologies (passive solar walls, lightweight concrete walls, ventilated or double-skin walls, and walls with latent heat storage), and three

conventional walls (wood-based walls, metal-based walls and masonry walls). Other authors focused on local façade systems. Theodosiou and Papadopoulos (2008) studied four scenarios with two configurations of wall thermal insulation that are frequently used in typical Greek buildings (double wall and single wall), in order to investigate the impact of thermal bridges on energy consumption. Yu et al. (2009) systematically evaluated the energy and thermal performance of residential envelopes in six typical multi-skin external walls in China. Aldawi et al. (2012) investigated the thermal performance of a new house wall envelope in Australia and defined a conventional house wall system (brick veneer and wood frame wall) and an alternative house wall system (reinforced concrete panel with insulation). Finally, Cuerda et al. (2014) developed a system for classifying the façades of buildings erected between 1950 and 1980, in a specific neighbourhood in Madrid (Spain).

In conclusion, existing classifications do not define the construction composition of the opaque part of façades. Some authors have carried out specific studies on façade classifications, without covering the entire range of façades in Spanish residential buildings. Consequently, a façade classification for housing stock in Spain was developed.

An initial façade classification proposal was developed by the research team according to the literature review and the national and regional regulations and codes related to buildings and construction processes. The initial classification system was composed of four levels, and took into account: (1) the materials in the core fabric and the external wall covering as the main level, (2) the existence of an air cavity and its position and type, when applicable, (3) the existence and position of insulation, and finally (4) the type of external wall covering system, since this is the part of the closures that is in direct contact with the aggressiveness of the external environment and, therefore, more susceptible to degradation processes. A workshop was held with a panel of experts to analyse, enhance and validate the proposed classification. The panel was composed of practitioners from the construction industry who are specialised in existing buildings: two professors from the Department of Architectural Technology II at the *Universitat Politècnica de Catalunya-BarcelonaTech* (UPC), two professors from the Department of Construction Engineering at the UPC, three building engineers from Spanish design firms who are specialised in existing buildings, and one quality manager from a Spanish construction company who is specialised in residential buildings.

At the start of the workshop, the panel of experts defined three premises to take into consideration: (1) comprehensiveness, which refers to the extent to which the classification can cover all the main categories and issues associated with types of façades; (2) functionality, which refers to the extent to which the façade classification can be used by different technicians to obtain the same results; and (3) suitability, which refers to the extent to which the classification facilitates energy studies. Then, the classification proposal was presented. To improve the comprehensiveness of the classification, proposals were made to modify its levels, based on original existing buildings in the Spanish area, without taking into account any measures that had been implemented to upgrade façades. Firstly, the panel of experts proposed using the number of skins as the main level, given that they considered that this first level of classification has a great impact on façades' energy performance. The experts agreed on

the levels referring to the existence of an air cavity and its position and type, and on the levels referring to the existence and position of insulation and to the type of external wall covering. These aspects also play an important role in the energy performance of the façades. In order to cover the typical types of façades in existing Spanish residential buildings, and to minimize the number of types, the experts agreed to take as variables the materials and the thickness of layers in the opaque part of façades. As a result, the classification was organised into four levels:

1. Number of skins of the façade. The main layer of façades is usually made of different types of ceramic or concrete bricks. The inner layer, in the case of double skin façades, is generally made of ceramic or concrete bricks, or laminated plasterboard.
2. Existence of air cavity. Façades may or may not have an air cavity. Air cavities can be ventilated (internally or externally) or non-ventilated.
3. Existence of insulation. Façades may or may not have insulation. Insulation can be placed on the outside of the main layer (external insulation) or inside the air cavity (internal insulation).
4. Type of external wall covering. Façades may be finished with a continuous covering, a non-continuous covering or faced (without a covering).

Table 1 presents the resulting façade classification for existing residential buildings in Spain.

Façades classification for existing residential buildings								Maximum <i>U-values</i> for heavy façades according to NBE-CT-79 (Spain 1979)					Maximum <i>U-values</i> for façades according to the Spanish Technical Building Code (Spain 2006)				
Number of skins		Air cavity		Insulation		Wall covering		Zone V	Zone W	Zone X	Zone Y	Zone Z	Zone A	Zone B	Zone C	Zone D	Zone E
F.1	Single skin	AC.1	Without air cavity	I.1	Without insulation	WC.1	Faced	1,80	1,80	1,60	1,40	1,40	0,94	0,82	0,73	0,66	0,57
						WC.2	Continuous covering										
						WC.3	Non-continuous covering										
		AC.2	With external ventilated air cavity	I.3	External	WC.2	Continuous covering										
						WC.3	Non-continuous covering										
						WC.3	Non-continuous covering										
F.2	Double skin	AC.1	Without air cavity	I.2	Internal	WC.1	Faced	1,80	1,80	1,60	1,40	1,40	0,94	0,82	0,73	0,66	0,57
						WC.2	Continuous covering										
						WC.3	Non-continuous covering										
		AC.2	With external ventilated air cavity	I.1	Without insulation	WC.3	Non-continuous covering										
				I.2	Internal	WC.3	Non-continuous covering										
		AC.3	With internal ventilated air cavity	I.1	Without insulation	WC.1	Faced										
						WC.2	Continuous covering										
						WC.3	Non-continuous covering										
				I.2	Internal	WC.1	Faced										
						WC.2	Continuous covering										
						WC.3	Non-continuous covering										
		AC.4	With non-ventilated air cavity	I.1	Without insulation	WC.1	Faced										
						WC.2	Continuous covering										
						WC.3	Non-continuous covering										
				I.2	Internal	WC.1	Faced										
						WC.2	Continuous covering										
						WC.3	Non-continuous covering										

Table 1. Classification of façades in existing residential buildings in Spain and maximum *U-values* for façades according to national regulations

2.2 CLASSIFICATION OF ANOMALIES THAT AFFECT THE FAÇADES OF EXISTING RESIDENTIAL BUILDINGS

Literature reviews were carried out to characterize all the anomalies that may occur in any type of façade and deteriorate its conservation state, in Spanish residential buildings.

Concerning external wall covering systems, Gaspar and Brito (2005) defined different levels of anomalies that can affect cementitious mortar renders such as staining, cracking, presence of fungi, efflorescence, dampness, damaged material, infiltrations, spalling of the surface, corrosion, ruptures, loss of adhesion between layers and detachments. Flores-Colen et al. (2008) characterised eleven types of stains in rendered walls as efflorescence / cryptoflorescence, carbonation, uniform dirt / non-uniform dirt, “ghost-like stains”, moisture, fungi/moulds, parasitic vegetation, corrosion, chromatic changes/ decolouration, graffiti and bird droppings. Silva et al. (2013) and Gaspar and Brito (2008) characterised anomalies that affect cement-rendered façades as staining, cracking and detachment. Neto and Brito (2011) classed anomalies in natural stone cladding into seven groups: four groups are related to anomalies in the cladding element (colour change, fracture and cracking, presence of biological or other elements and loss, volume change or deterioration of the stone); and three groups are related to elements of the cladding system (loss of adherence or loosening of the stone slab, joint anomalies and anomalies in the fixing elements). Pires et al. (2013) classified fourteen types of anomalies in painted rendered façades in five groups that distinguish between the various forms of pathological manifestation: adherence to the substrate anomalies, film cohesion anomalies, colour anomalies, stains and texture anomalies. Amaro et al. (2013) classified eighteen types of anomalies in External Thermal Insulation Composite Systems (ETICS) in three groups: materials rupture anomalies, colour/ aesthetic anomalies, and flatness anomalies. Along the same line, Silvestre and Brito (2009, 2011) classified anomalies that affect adherent ceramic tiling systems on façades into four groups, namely: detachment of the adherent ceramic tiling outer layer, cracking of the adherent ceramic tiling outer layer, deterioration of the tiles, and aesthetic anomalies.

In relation to anomalies that affect façades as a construction element, Monjo (1988) classified nine types of damage in a statistical study of the construction pathology of urban façades in Madrid: dampness, cracks, fissures, detachments, erosion, efflorescence, corrosion, dirtiness and biological organisms. Chew and Silva (2004) defined types of anomalies in US traditional façade systems as cracking, blistering, corrosion, peeling and flaking, chipping, spalling, discoloration, delamination, staining, biological growth, sealant/joint failure, efflorescence and dampness. Finally, Rodrigues et al. (2011) identified the main anomalies in façades as discolouring and detachment, cracks, efflorescence spots and dark spots, and dampness. Likewise, the UNE 41805-10 IN: 2009 (AENOR 2009) report defines three groups of pathological processes that can affect façades: physical processes (dampness, dirtiness and physical erosion), mechanical processes (cracks, fissures, detachment and mechanical erosion) and chemical processes (efflorescence, biological organisms, corrosion and chemical erosion).

Regarding classifications of anomalies in building elements, Monjo (2007) grouped construction failures that damage construction materials and building elements into three families: physical (dampness, dirtiness and erosion), mechanical (deformation, rupture, detachment and erosion) and chemical (efflorescence, corrosion, biological organisms and erosion). Craig et al. (2010) organised snagging-related items in the private house building sector under the three headings of technical quality, aesthetic issues and omissions, but they did not identify the construction element to which the anomalies referred. Ahzahar et al. (2011) ranked a relative index for common types of building anomalies and failures in construction projects in Malaysia as blemishes, corrosion of reinforced steel, damage of the exterior surface, dampness, peeling paint, roof anomalies, cracking, spalling or chipping, foundation failure and structure instability.

The literature review did not reveal a unified classification system. Therefore, a system for classifying anomalies was developed and codified on the basis of the review. The initial proposal was comprised of a one-level category with nineteen anomalies that covered all of the defects found in the review. During the workshop, the initial anomaly classification was analysed, enhanced and validated by the same panel of experts, using the same methodology as that applied in the façade classification for existing residential buildings. The anomaly classification was developed taking into account the abovementioned premises: (1) comprehensiveness, (2) functionality, and (3) suitability.

In the workshop, experts considered two ways to minimize the number of categories required to search functionality, in accordance with Mills et al. (2009). The first concerned differences in the levels of detail of the anomalies, which can be either specific or generic. Experts suggested grouping specific anomalies that have analogous consequences on the level of degradation of façades. This solution affected the degradation of materials category, which included the initial categories of chemical, physical and mechanical erosion, biological organisms, efflorescence, dirtiness and staining. The second concerned the elimination of anomalies that had no influence on the level of degradation of façades, as they were purely aesthetic and did not reduce the quality of façade elements or materials. As a result, aesthetic anomalies, graffiti and discoloration or brittleness were removed as a category. Furthermore, in accordance with Macarulla et al. (2013), the experts agreed to include only singular words to standardize the vocabulary.

The resulting anomaly classification has eight categories: (1) adhesion failure, (2) cracking, (3) dampness, (4) deformation, (5) degradation of material, (6) detachment, (7) oxidation and corrosion, and (8) rupture. These categories cover potential damage that can affect the state of conservation of elements or materials in the façades of existing residential buildings. Table 2 presents the anomaly classification for closures in residential buildings and its definition.

Category		Definition
D.1	Adhesion failure	Lack of junction between a material that mainly serves as a coating and its support, without detachment.
D.2	Cracking	Longitudinal division that affects the surface of a construction element, and can be continuous, non-continuous or involves the total thickness of the element.
D.3	Dampness	Presence of water in higher proportions than expected in a material or a building element.
D.4	Deformation	Loss of the original shape of the element.
D.5	Degradation of material	Reduction in the quality of an element, without affecting its functionality. This may occur as a result of staining, erosion, dirtiness, etc. and is due mainly to a lack of maintenance.
D.6	Detachment	Lack of continuity of a coating on the wall, as a result of either constant degradation of a material or adhesion failure.
D.7	Oxidation and corrosion	Chemical reaction generally produced in metals by the presence of oxygen. The reaction is usually increased by moisture. In corrosion, the material is gradually destroyed.
D.8	Rupture	Absence of material that is not caused by continuous degradation, and appears in bulky items.

Table 2. Classification of anomalies damaging façades in existing residential buildings in Spain

2.3 DETERMINATION OF THE RELATIONSHIP BETWEEN FAÇADES AND THE ANOMALIES THAT AFFECT THEIR STATE OF CONSERVATION IN EXISTING RESIDENTIAL BUILDINGS

The relationship between façades and the anomalies that affect, or can affect, each type of façade were analysed, to facilitate an accurate, systematic analysis of the energy impact of closures' state of conservation on building thermal performance.

A second workshop was held with the same panel of experts to discuss an initial proposal. The results showed that cracking, dampness, deformation, degradation of material, and oxidation and corrosion anomalies can affect all types of façades. Adhesion failure and detachment anomalies can damage types of façades with continuous and non-continuous external covering, but do not affect faced façades. Rupture can affect types of façades with non-continuous external covering and faced façades, but does not affect façades with external continuous covering. Table 3 shows the types of anomalies that affect, or have the potential to affect, the state of conservation of each type of façade.

Façade classification for existing residential buildings ^a				Anomaly classification for façades in existing residential buildings ^b							
Number of skins	Air cavity	Insulation	External wall covering	D.1	D.2	D.3	D.4	D.5	D.6	D.7	D.8
F.1	AC.1	I.1	WC.1		x	x	x	x		x	x
			WC.2	x	x	x	x	x	x	x	
			WC.3	x	x	x	x	x	x	x	x
	AC.2	I.3	WC.2	x	x	x	x	x	x	x	
		I.1	WC.3	x	x	x	x	x	x	x	x
		I.3	WC.3	x	x	x	x	x	x	x	x
F.2	AC.1	I.2	WC.1		x	x	x	x		x	x
			WC.2	x	x	x	x	x	x	x	
			WC.3	x	x	x	x	x	x	x	x
	AC.2	I.1	WC.3	x	x	x	x	x	x	x	x
		I.2	WC.3	x	x	x	x	x	x	x	x
	AC.3	I.1	WC.1		x	x	x	x		x	x
			WC.2	x	x	x	x	x	x	x	
			WC.3	x	x	x	x	x	x	x	x
		I.2	WC.1		x	x	x	x		x	x
			WC.2	x	x	x	x	x	x	x	
			WC.3	x	x	x	x	x	x	x	x
	AC.4	I.1	WC.1		x	x	x	x		x	x
			WC.2	x	x	x	x	x	x	x	
			WC.3	x	x	x	x	x	x	x	x
		I.2	WC.1		x	x	x	x		x	x
			WC.2	x	x	x	x	x	x	x	
			WC.3	x	x	x	x	x	x	x	x

^a Façade codes can be found in Table 1.

^b Codification of anomalies for façades obtained from Table 2.

Table 3. Relationship between façades and anomalies that affect their state of conservation

3. CASE STUDY AND DISCUSSION

A case study was performed to verify the aforementioned associations between types of façades and their anomalies.


As in Mills et al. (2009) and Macarulla et al. (2013), data were obtained from an organisation's database. In this case, the database contained a collection of technical

reports generated by the UPC's Building Laboratory. The reports give textual descriptions of damage affecting buildings and a set of pictures illustrating the anomalies (Fig. 2). The case study included 154 public housing buildings located in Barcelona and erected between 1800 and 2005 (Table 4). Residential buildings erected after 2006 were not inspected, since they are relatively new and should not have any anomalies resulting from the passage of time. The buildings were grouped by year of construction (built before and after 1980). Residential buildings that were built before 1980 in Spain did not have to comply with any thermal requirements, and therefore most buildings from this period do not have any insulation. Residential buildings built between 1980 and 2006 fall under the thermal requirements established by NBE CT 79. The use of cavity walls with thermal insulation in the cavity was very common in this period. Façades are usually rendered and painted. Table 1 shows typical *U-values* for these buildings (Gangoells and Casals 2012). New residential buildings added to building stock between 2007 and 2010 were built under the new thermal requirements established by the TBC (Table 1). Construction techniques and systems used during the previous period are still very common. However, a thicker insulation layer and higher performance insulation materials are used to meet the higher requirements (Gangoells and Casals 2012). Table 4 describes the main characteristics of the analysed buildings. A total of 216 types of façades were identified in the 154 public housing buildings, as some buildings were found to have more than one type of façade. The types of façades in residential buildings were identified through visual inspection and knowledge of traditional building techniques used in the construction period (City Council of Barcelona 2002). The sample of buildings analysed included all the types of façades that had been identified in the section "Classification of façades in existing residential buildings". Single-skin façades without an air cavity and with external insulation and continuous covering (code F.1-AC.1-I.3-WC.2), and single-skin façades with an external ventilated air cavity, external insulation and non-continuous covering (code F.1-AC.2-I.3-WC.3) were types of façades that resulted from the refurbishment of buildings' envelopes. By the end of the case study, all of the analysed façades had been classified.

Year of construction	Number of buildings	Number of dwellings	Floor area (m ²) ^a	Number of storeys above ground
< 1980	73	608	94,206.00	From 3 to 7
From 1980 to 2005	81	818	89,728.00	From 4 to 7
Total	154	1,426	183,934.00	-

^a Data obtained from the Spanish Cadastral Electronic Site (Spanish Ministry of Finances and Public Administration 2009).

Table 4. Characteristics of the Case Study

Identification of facade							
			Location:	Main facade, Side facade 1 and Side facade 2			
			Description:	External wall covering			
			Typology:	Continuous			
			Material:	Stucco			

Identification of anomalies							
ELEMENT		State	T / Es	F	DM	O	B
			P i L i G	P i L i G	P i L i G	P i L i G	P i L i G
COVERING SYSTEM	Non-continuous covering	I					
	Mortar render	X		3			
	Faced						
	Single layer coating						
	Painted surface	X	2		2		
	Other:						


Description of anomalies							
			Photographic reference:	_01			
			Location:	Main facade			
			Element:	Mortar render			
			Defect:	Detachment			
			Magnitude:	Isolated			
			Intervention:	2			

Fig. 2. Samples of technical reports provided for the case study (photographs by the UPC's building laboratory)

Once all of the façades had been classified, the anomalies were mapped using the data and pictures contained in the technical reports on the analysed buildings. As façades may have more than one type of anomaly, a total of 262 types of anomalies that damage the opaque part of façades were found. A total of 121 façades were found to be affected by degradation of materials (352 cases were found), 49 façades were affected by cracking (found in 582 cases), and 33 façades were affected by detachment (245 cases found). A total of 79 occurrences of oxidation and corrosion were found in 27 façades, and 59 cases of rupture were found in 11 façades. Adhesion failure was found in 71 cases distributed in 11 façades, 8 façades were affected by dampness (found in 18 cases) and 2 façades were affected by deformation (a total of 2 cases were found). Sixty façades had no anomalies related to the object of the study, which does not mean they do not have anomalies in other parts of the façade, such as balconies or windows. All the types of anomalies included in the section “Classification of anomalies that affect the façades of existing residential buildings” were found in the sample. Similarly, all the anomalies that affected closures in the sample of façades could be explained within the established classification. Thus, possible relationships between types of façades and the

types of anomalies that can damage them were verified. Table 5 shows the number of façades of each type covered by the case study, the number of façades affected by each type of anomalies, and the number of façades that were not affected by any anomalies. A lack of relationship between types of façade and types of anomalies is marked with a cross.

Façade classification for existing residential buildings ^a				Number of façades	Anomaly classification for façades in existing residential buildings ^b								Number of façades without anomalies
Number of skins	Air cavity	Insulation	External wall covering		D.1	D.2	D.3	D.4	D.5	D.6	D.7	D.8	
F.1	AC.1	I.1	WC.1	2	x ^c	0	0	0	2	x	1	0	0
			WC.2	35	5	14	2	2	15	15	14	x	9
			WC.3	2	0	1	0	0	1	0	0	0	1
	AC.2	I.3	WC.2	3	0	2	0	0	3	1	0	x	0
		I.1	WC.3	1	0	1	0	0	1	0	0	0	0
		I.3	WC.3	1	0	0	0	0	0	0	0	0	1
F.2	AC.1	I.2	WC.1	20	x	3	2	0	5	x	0	2	12
			WC.2	40	0	5	2	0	39	0	0	x	1
			WC.3	7	1	1	0	0	7	0	0	0	0
	AC.2	I.1	WC.3	2	0	0	0	0	2	0	0	0	0
		I.2	WC.3	1	0	1	0	0	1	0	0	1	0
	AC.3	I.1	WC.1	2	x	0	0	0	1	x	0	0	1
			WC.2	9	1	1	0	0	7	1	1	x	0
			WC.3	7	0	0	0	0	2	2	0	5	0
		I.2	WC.1	2	x	1	0	0	0	x	1	0	1
			WC.2	7	0	4	0	0	4	1	0	x	2
			WC.3	6	1	0	0	0	2	0	1	2	2
	AC.4	I.1	WC.1	9	x	0	0	0	2	x	0	0	7
			WC.2	19	3	7	1	0	12	8	1	x	2
			WC.3	3	0	1	0	0	1	0	0	0	2
		I.2	WC.1	11	x	0	0	0	1	x	0	0	10
			WC.2	23	0	6	1	0	11	4	8	x	9
			WC.3	4	0	1	0	0	2	1	0	1	0

Note: Anomalies refer only to the opaque part of façades. x = lack of relationship between type of façade and type of anomaly.

^a Façade codes can be found in Table 1.

^b Codification of anomalies for façades can be found in Table 2.

Table 5. Number of façades affected by types of anomalies

Within the sample, all types of closures were found to be affected by anomalies that had an impact on their state of conservation, except single-skin façades with an external

ventilated air cavity, external insulation and non-continuous covering (code F.1-AC.2-I.3-WC.3). This type of façade was not affected by any anomaly, but the sample only included one recently refurbished façade, according to the pictures included in the technical report. During the mapping, all the existing relationships were verified for the type of single-skin façade without an air cavity or insulation, finished with continuous covering (code F.1-AC.1-I.1-WC.2).

Since coatings are the outermost part of façades and are thus very susceptible to damage, anomalies affecting closures were analysed by external coating type. It was observed that the three types of external wall covering were affected by all the types of anomalies established in the section “Classification of anomalies that affect the façades of existing residential buildings”, except deformations (D.4), which were only observed in façades finished with continuous covering.

Deformations were the least frequent anomaly. This may be due to the fact that they are generated not only by the effects of the environment and lack of maintenance, but also by other situations involving risk, for instance, problems with material behaviour, movements of the building or structural issues.

4. CONCLUSIONS

In this study, a classification system for façades and the anomalies that affect the envelope’s conservation status in existing Spanish residential buildings was developed for the first time. The findings will be a starting point for a future analysis on the gap between the predicted and actual energy performance of existing residential buildings due to façade conservation status.

The façade classification for existing residential buildings was based on the opaque part of closures and organised into four levels: number of skins, existence of an air cavity, existence of insulation and type of external wall covering. The research covered original buildings in the Spanish area and did not take into account any measures to upgrade the façades. Twenty-three types of façades were identified, depending on the type of material and thickness of the different layers comprising the building closures. The anomaly classification had eight categories: adhesion failure, cracking, dampness, deformation, degradation of material, detachment, oxidation and corrosion, and rupture. During a workshop with a panel of experts, both classifications were found to be comprehensive, functional and suitable.

To determine the types of anomalies that affect, or have the potential to affect, the state of conservation of each type of façade, a relationship between the classifications was established. This relationship was validated by the same panel of experts in a second workshop.

The classification system can be applied to most Spanish buildings. The comprehensiveness of the classification system was demonstrated with a case study, using real data on 154 public housing buildings. All the closures in the sample of buildings were covered by the classification system, and all the façades in the

classification system were found in the sample of buildings. Furthermore, all the anomalies affecting façades in the sample of buildings were found in the classification system, and all the types of anomalies established in the classification system were identified in the sample of façades.

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